the economic viability of SNG but locking in its extensive environmental costs.

Price decontrols and institutional reforms in China could similarly make conventional and unconventional natural gas cheaper and more abundant, reducing costs and environmental consequences, including GHG emissions, water demands and air pollution, compared to SNG[14]. Conventional and unconventional natural gas use come with their own environmental impacts, but they have a substantially smaller carbon and water footprint than SNG. In addition, the broad implementation of SNG could slow the deployment of renewable capacities that have even smaller carbon and water footprints and that generate less air and water pollution (acknowledging that China's renewable energy production is expanding rapidly today).

At a minimum, Chinese policymakers should delay implementing their SNG plan to avoid a potentially costly and environmentally damaging outcome. An even better decision would be to cancel the program entirely. ❐

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COMMENTARY:

Bias in the attribution of forest carbon sinks

Karl-Heinz Erb, Thomas Kastner, Sebastiaan Luyssaert, Richard A. Houghton, Tobias Kuemmerle, Pontus Olofsson and Helmut Haberl

A substantial fraction of the terrestrial carbon sink, past and present, may be incorrectly attributed to environmental change rather than changes in forest management.

In the late nineteenth and early twentieth centuries, forest areas were much smaller and forests more strongly degraded than today in most regions that are now industrialized. During industrialization, fossil fuels replaced fuelwood and chemical fertilizers allowed farmers to reduce or abandon practices such as forest grazing and litter raking. Are these changes in forest management important enough to change our current understanding of the forest carbon sink, and perhaps even the global terrestrial carbon balance?

Terrestrial ecosystems play two roles in the global carbon balance[1–4]. First, land use, land-use change and forestry (LULUCF) are resulting in net emissions of carbon to the atmosphere, mainly driven by deforestation. Second, the global carbon balance requires a residual terrestrial carbon sink, which was negligible before ~1950 but has been growing ever since[5]. That residual sink is determined by difference from the other terms in the global carbon balance (that is, atmospheric carbon concentration, emissions from fossil fuel combustion and LULUCF and known land and ocean sinks). The residual sink has been attributed to the effects of environmental change (for example, climate, CO_2 and nitrogen deposition) on terrestrial carbon storage[2,3,5], but its location, causes and exact magnitude are uncertain. If the emissions from LULUCF are overestimated, so is the residual terrestrial sink.

Book-keeping models are widely used to quantify the effects of LULUCF on regional to global carbon fluxes[6–8]. Generally, these models assess vegetation responses to land-cover changes and wood harvest on a yearly basis, using constant values of standing biomass at harvest time to calculate areas subject to clearing and regrowth (for details see Supplementary Information). Book-keeping models reflect only LULUCF effects. They are commonly used to separate LULUCF and environmental effects — for example, by contrasting C flows calculated by book-keeping models with forest-inventory derived results[9], or results from atmospheric measurements[2–4] (both of which include environmental and land-use effects). Based on these approaches, it is generally estimated that global net annual carbon emissions resulting from LULUCF were 1.1±0.2 Pg C yr^{-1} between 1990 and 2009 (including flows from deforestation and forest regrowth)[8], contrasted by a terrestrial net sink of approximately 1.4 Pg C yr^{-1}. The resulting global residual sink, necessary to close the terrestrial balance, is estimated at 2.5±0.8 Pg C yr^{-1}.

Here, we show that calculations of Austria's carbon balance with a book-keeping model severely underestimate both the forest carbon sink and past harvested areas, which is likely to result in a biased attribution of observed sinks and sources. We applied one of the most widely used book-keeping models[7,10] to reconstruct the carbon sink of Austria's forest between 1830 and 2010 and contrasted the model results with an inventory-based reconstruction of carbon fluxes. Historical databases and century-long archives on forestry practices are available for Austria and were used to establish the carbon sink between 1830 and 2000[11,12] (Supplementary Information). This makes Austria a unique and ideal case for the aims of this study. We focus on carbon flows in forest vegetation, excluding carbon stored in soils and wood products.

The inventory-based reconstruction confirmed that vegetation increasingly acts as a strong carbon sink throughout the twentieth century (Fig. 1a). Natural disturbances such as forest fires, storms and insect outbreaks played a minor role in Austria throughout the period. By 2000, the 41,000 km² of forests in Austria absorbed 6.8 Tg C yr⁻¹. When using the default parameter settings, the model predicted a carbon source of 0.9 Tg C yr⁻¹ for the same year, in stark contrast to the observed sink (Fig. 1a,b). Alternative model versions in which the default values for carbon stocks of harvested forests[10] were replaced by Austria-specific carbon-stock data[11–13] did not substantially change the results (Fig. 1a,b and Supplementary Information). All alternative model runs resulted in net emissions ranging from 0.8 to 1.6 Tg C yr⁻¹ in 2000 and thus failed to reproduce the trend, magnitude and even the direction of the reconstructed carbon sink.

In the classic interpretation, the 'residual' sink of 7.7 Tg C yr⁻¹ in 2000 (that is, the difference between the source of 0.9 Tg C yr⁻¹ as predicted by the model and the sink of 6.8 Tg C yr⁻¹ as estimated from the forest inventory), is driven by environmental effects. Carbon gains resulting from the observed 24% expansion in forest area (that is, 7,600 km²) played a minor role (Supplementary Information). Dynamics in natural forests did not play a significant role in this regard, owing to the region's long land-use history[11,14] and the subordinate portion of natural or unmanaged ecosystems in Austria (Supplementary Information). Thus, the main underlying mechanism was an increase in carbon density in managed forests, resulting from biomass growth (net annual increment) being larger than wood harvest and natural losses.

An adjusted model architecture that allowed accounting for increases in carbon density (by using varying values for standing biomass at harvest time) was able to reproduce the trajectory of the reconstructed carbon stocks in forests (Fig. 1b). The observed trend in carbon storage in Austrian forests was best reproduced

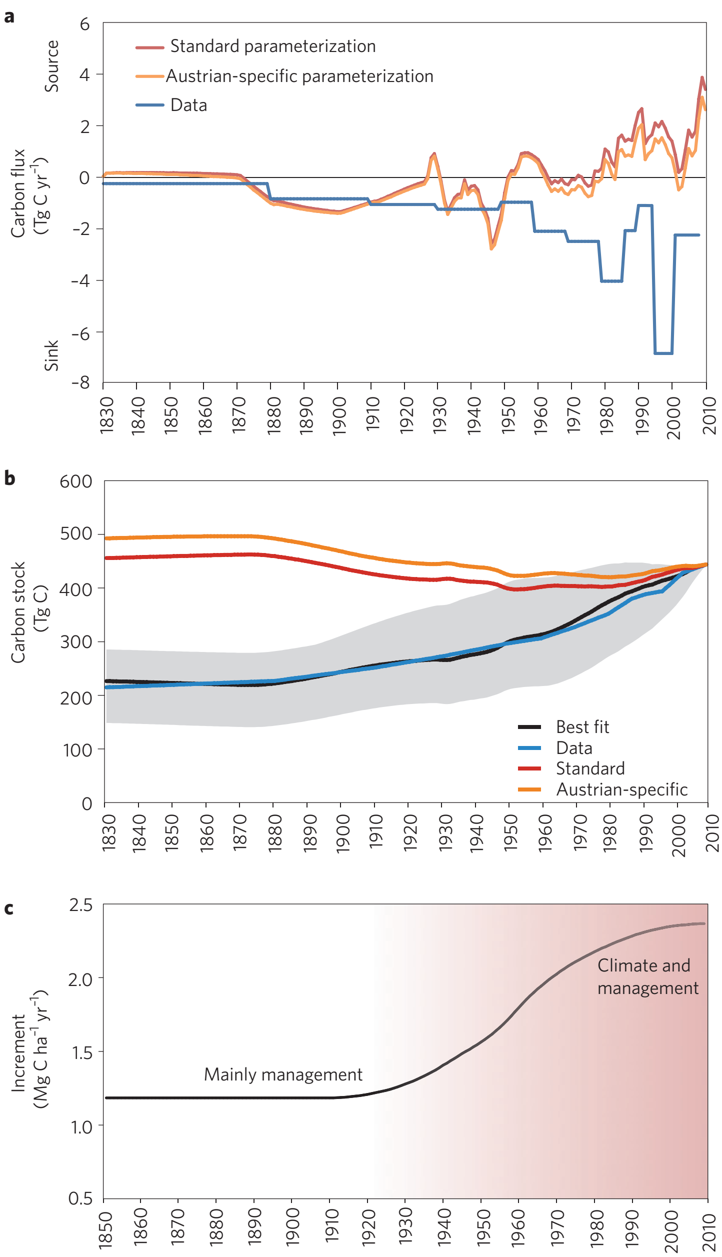

Figure 1 | Model-based reconstruction of carbon flows and stocks in Austria's forests from 1830–2000. **a**, Carbon flux calculated from the book-keeping model, with the standard parameterization for standing biomass at harvest time of 105 Mg C ha⁻¹ (refs 6,7) and Austria-specific value of 177 Mg C ha⁻¹. These constant values for standing biomass do not reproduce the carbon flux in Austria's forests[11,22]. The data flux is the first derivative of the data-based total carbon stock in forests in figure 1b, blue line. **b**, Back-casting of trends in carbon stocks in forests by application of the standard and Austria-specific parameterizations of the book-keeping model, and by implementing changes in the standing biomass at harvest time. The grey shading indicates the envelope of the top 20 model runs, modulating the standing biomass at harvest time from the known value in 2008[11,22]. The best-fit model run was estimated with standing biomass per unit area increasing by 50% starting in 1910. **c**, Based on this finding, the increase of mean annual increment of Austria's forests for the best-fit model run is shown, indicating that a large fraction (32%) of this increase occurred before 1950. This is due to management change (white area); the red shading indicates an increasing likelihood of influences resulting from climate change.

(see Supplementary Information) by assuming that the standing biomass at the time of harvest was increasing from 1960 onwards from an initial value of 88 Mg C ha^{-1}, 50% lower than the value in 2010 (177 Mg C ha^{-1}), which implies that annual wood increment already started to increase in 1910 (Fig. 1c), owing to the time between stand regeneration and harvest.

The question then is why wood increment began to increase so strongly after 1910, which is well before the increase in atmospheric CO_2 became apparent, and well before environmental change had a noticeable effect on forest growth. We suggest that this early increase provides clear evidence that part of the 'residual' sink can be attributed to changing land-use practices and not environmental change. For Austria, as well as for most parts of Central Europe, it is well documented that non-timber forest uses (for example, livestock grazing in forests and the use of twigs, leaves and litter as bedding in stables) were widespread and substantial in the early nineteenth century, but lost importance during the early twentieth century[14–16]. Cessation of these practices together with improved forest management (including species selection) allowed for improvements in the growing conditions for trees. The increase in wood increment from 1.7 Mg C yr^{-1} ha^{-1} in 1910 to 3.5 Mg C yr^{-1} ha^{-1} in 2000 according to our best-fit run implies that a large fraction of this increase occurred before 1950 (Fig. 1c) and is hence most probably attributable to changes in forest management. This substantial underestimation of management effects suggests that approaches used at present do not correctly evaluate the effects of LULUCF on the terrestrial C balance, and thus calls into question current estimates of the magnitude of the 'residual sink' that is commonly attributed to environmental drivers.

Our study shows the importance of implementing a dynamic carbon density at the time of harvest into LULUCF models to adequately assess the net effects of land use on climate: larger carbon stocks directly translate into smaller surface areas cleared for the same amount of harvest. This influences estimates of the effects of other key climatic variables such as reflected solar radiation, evapotranspiration or roughness length. Land-use effects other than forest harvest need to be considered for more accurate simulations of carbon storage and land–atmosphere interactions, in particular the dynamic interrelation between harvest rates and standing biomass at harvest time[17], as well as non-timber forest uses, species selection and optimized planting, as exemplified by the Austrian case study.

A bias in attribution towards environmental effects similar to the one found here can be expected in large areas in the humid temperate zone: large areas of Europe, North America and temperate Asia show a similarly long-term land-use history characterized by a reduction or even almost complete abandonment of non-timber uses such as pollarding, pruning, litter raking and forest grazing (Supplementary Table S2). Thus, the effects of land use on land–atmosphere flows of carbon are likely to be much larger than assumed today.

Our findings support recent claims that terrestrial ecosystems provide a carbon sink if their carbon stocks had previously been depleted by past human use and are now recovering due to changes in management[12,18]. As overuse of forests is a widespread phenomenon in developing countries[19], these results suggest that over short to medium time spans the potential for strategies such as (Reducing Emissions from Deforestation and forest Degradation)[20] may be larger than is often thought. However, if forest carbon sinks should contribute to overall climate change mitigation, new ways for realizing such effects in forests need to be found, because in the past a transition towards fossil fuel energy (both directly as fuel, and indirectly for the production of agricultural inputs such as chemical fertilizers and pesticides) was a prerequisite for the changes in management that have resulted in the carbon sink analysed in this study[12].

To summarize, we find that a substantial fraction of today's carbon sink is now incorrectly attributed to environmental change when, instead, it probably results from changes in management practices. Accurate attribution is critical for the development of robust land-use-related policies to mitigate climate change and avoidance of possibly ineffective (if not counterproductive) measures. This requires interdisciplinary efforts that aim to integrate earth science approaches and models with knowledge about societal transformations, such as long term socio-ecological research[21]. ❐

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Additional information

Supplementary information is available in the online version of the paper.